

# Future Water Cherenkov Detectors

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**Abstract.** In these proceedings a review of the current proposed large-scale Water Cherenkov experiments is given. An argument is made that future water Cherenkov detectors would benefit in the investment in neutron detection technology. A brief overview will be given of proposed water Cherenkov experiments such as HYPER-K and MEMPHYS and other R&D experiments to demonstrate neutron capture in water Cherenkov detectors. Finally, innovation developed in the context of the now defunct LBNE Water R&D option to improve Water Cherenkov technology will be described.

**Keywords:** Water Cherenkov Detector, neutron tagging, super-nova, light collection improvements

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## INTRODUCTION

The field of neutrino physics has made great strides with the advent of Water Cherenkov detectors leading to the original confirmation of neutrino oscillations from the atmospheric neutrino measurement at Super-Kamiokande [1]. While this technology is considered more than mature, it offers an efficient way to tackle the search for traditional proton decay modes (such as  $p \rightarrow e^+ \pi^0$ ) which require a larger mass of detector than is currently available with the Super-Kamiokande detector. There are debates on the importance of having neutron detection opportunities for this type of detector, since they require additional costs with little impact on the current scientific “hot-topic” objectives. There are however two significant advantages to having neutron detection opportunities: (a) it can open the door to precise measurement of proton decay by significantly reducing backgrounds from atmospheric neutrinos through a more precise understanding of Final State Interactions (FSI’s) [via neutron tagging] and (b) it provides opportunities to measure anti-neutrinos from a super-nova collapse; these anti-neutrinos composes the majority of the expected signal.

## NEUTRINO OSCILLATION PARAMETERS AND OTHER SCIENCE GOALS

We currently have a good understanding of most of the 3-flavor oscillation parameters ( $\Delta m_{12}^2, \Delta m_{13}^2, \Delta m_{23}^2, \theta_{12}, \theta_{13}, \theta_{23}$ ). However, the CP violation phase, the mass hierarchy and the absolute mass scale of the neutrino remain a mystery. A measurement of the CP violation phase require long baseline and three competing programs are underway to measure this phase, one is a water Cherenkov detector, one is a large scale liquid Argon detector and one is a large scale liquid scintillator (Hyper-Kamiokande, LBNE, LENA). Water Cherenkov may have advantages due to its increased size compared to other experiments leading to a more sensitive proton decay search and increase supernova detection opportunities.

## Proton Decay

Interactions such as the traditional proton decay mode  $p \rightarrow e^+ \pi^0$  have been elusive in Super-Kamiokande and claims have been made that this mode may be less favorable than the  $p \rightarrow \bar{\nu} K^+$  mode due to super symmetry arguments. However, the sensitivity to the proton decay channel  $p \rightarrow \bar{\nu} K^+$  is low in water Cherenkov Detector since the daughter kaon is below the Cherenkov threshold. If the kaon is “invisible” in the detector, this mode is nearly indistinguishable from atmospheric neutrinos events, however a tagging of gamma-ray emission (between  $6 \sim 9$  MeV) can provide some signal tagging. There are two other solutions to this issue: (a) tag neutrons from atmospheric neutrino events to significantly reduce the background and (b) introduce a small amount of scintillator that enable the detection of kaon which in turn allows a triple coincidence analysis ( $K \rightarrow \mu \rightarrow e$ ). For the traditional modes (e.g.:  $p \rightarrow e^+ \pi^0$ ),

the evaluation of FSI show that a minority (9%) of branching ratios have outgoing neutrons; alternatively, the current estimates of Super-K is an average of 2 neutrons per neutrino at the proton decay energy [2]. A precise tagging of these neutrons is important in reducing backgrounds to a proton decay search. As will be explain later, US efforts are underway to understand this neutrino induced neutron production in oxygen.

## Supernova

The physics of supernova collapse is still not fully understood. The rarity of such events should be a motivating factor in the development of the next large scale water detectors. As is shown in Table 1, the production of anti-neutrino by inverse beta decay on hydrogen is the leading signature [3]. Finding ways of tagging the neutron from this interaction will provide important opportunities to understand the core collapse signature. One can expect 300 to 470 antineutrinos per kiloton from a burst and the anti-neutrino reaction dominate over the neutrino interactions.

**TABLE 1.** Event rates for different models in 100 kton of water, for the 30% PMT coverage detector configuration [3].

Channel	Events, “Livermore” model	Events, “GKVM” model
$\bar{\nu}_e + p \rightarrow e^+ + n$	27116	16211
$\nu_x + e^- \rightarrow \nu_x + e^-$	868	534
$\nu_e + {}^{16}\text{O} \rightarrow e^- + {}^{16}\text{F}$	88	379
$\bar{\nu}_e + {}^{16}\text{O} \rightarrow e^+ + {}^{16}\text{N}$	700	490
$\nu_x + {}^{16}\text{O} \rightarrow \nu_x + {}^{16}\text{O}^*$	513	124
Total	29285	17738

## OVERVIEW OF PROPOSED LARGE WATER CHERENKOV EXPERIMENTS

There are significant challenges to building a megaton size detector. These include light attenuation concerns, optimizing light collection coverage [or photomultiplier tube (PMT) coverage], and most importantly cost. The PMT coverage of an experiment has a direct correlation to the hardware energy threshold and this in turn has implications on the low energy physics one can do. At 40% coverage, a hardware threshold of 3.5 MeV could be obtained, allowing neutron detection of some neutron capture on Hydrogen. At 20% coverage, it was estimated that a hardware energy threshold of only 5.5 MeV could be attained: in this scenario, efficient neutron detection on Hydrogen is not possible [4].

## Hyper-Kamiokande

Hyper-Kamiokande is the only next generation experiment that has water as a first option [5] (LBNE is concentrating on liquid Argon and LAGUNA on liquid scintillator). The proposed detector is a 0.99 Megaton total volume with 99,000 20-inch PMTs for the inner detector leading to 20% light coverage. This will result in a total fiducial volume of 0.56 megaton; the detector is separated in 10 compartments of 56 kiloton each. The physics goals include some sensitivity to the mass hierarchy determination, good supernova sensitivity and proton decay sensitivity of  $\sim 10^{35}$  years for the  $p \rightarrow e^+ \pi^0$  mode and  $\sim 10^{34}$  years for the  $p \rightarrow \bar{\nu} K^+$  mode over 10 years.

## MEMPHYS

Part of the Laguna Design study included a second option detector composed of 2 modules of 103m height and 65m diameter under a rock overburden of 4800 m.w.e. at the Frejus mine. These two modules would be imaged by a total of 81,000 12” PMTs to reach 30% coverage in a total of 500 kton of fiducial volume. Alternatively, a 40% coverage with 20” PMTs is also considered [6].

## Lessons from LBNE's Water R&D

Early in 2012 a technology decision was made on the US effort for beam line physics. The choice were between a large TPC filled with liquid Argon (LAr) or a next generation 0.5 megaton Water Cherenkov detector. What was proposed at the technology decision was a 200 kton fiducial volume (FV) at the 4850 ft level with 29,000 PMTs covering an area of 9.8%. It was considered less costly to improve this initial coverage with light collector instead of investing in the purchase of more PMTs. It was estimated this detector could attain a 20% coverage with a smaller PMT size relative to SK-II which would have resulted in a 30% finer granularity. While both technology had strengths and weaknesses, this water option was not chosen. However, the work done for the water R&D [4] is beneficial for future water Cherenkov development such as Hyper-K or MEMPHYS and some of the highlights from this work is presented below.

### High quantum efficiency (HQE) phototubes

An improvement in light collection can be obtain with getting better quantum efficiency per phototubes and such a phototube was studied: the Hamamatsu 12-inch R11780 PMT showed a 52.4% increase in light collection at 400 nm [7] and showed charge and timing response that were uniform across most of the photocathode surface.

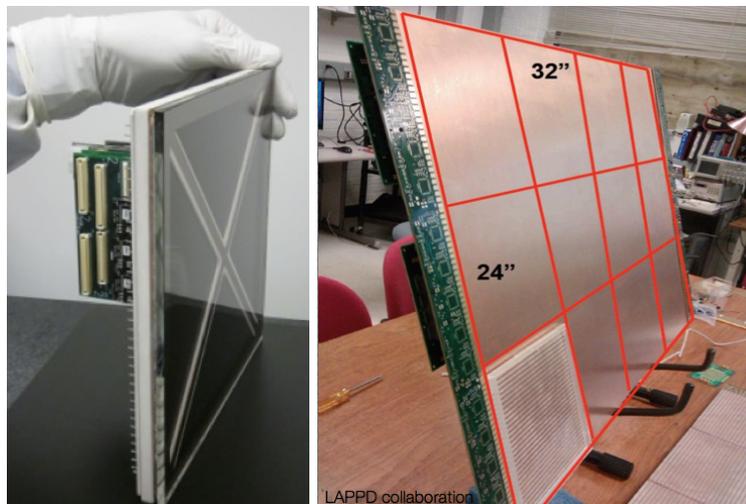
### Winston Cones

Winston cones were studied with a goal of a 40% light collection increase. They offer a lower alternative to additional PMTs (\$50 compared to \$3000 for a PMT) and have a proven track record in previous experiments such as SNO, Borexino-CTF. There are some concern that need to be addressed such as the risk of degradation in the water volume, limitation of the field of view, and vertex reconstruction and fiducial volume determination may be affected due to the position dependance of the light collector.

### Wavelength Shifter Plates

Wavelength shifter plates were also studied with a goal of a 40% light collection increase. Square plates have a proven track record in the IMB experiment and in the outer-veto of Super-K. The plates investigated were circular and 3 models were studied: Bicron BC482a (decay time 7 ns), BC499 and Eijen299 (~2 ns). Plates that change blue light to green may be used to "sharpen" the Cherenkov ring due to the absorption of Rayleigh scattered light. One of the concern is related to the timing delay which may impact vertex reconstruction. Different shape options and further test on material compatibility with water are underway at UC Davis.

### Large-Area Picosecond Photo-Detectors



**FIGURE 1.** On the left, a single LAPPD module. On the right, a series of LAPPD modules.

One of the most promising improvement is in the current development of Large-Area Photo-Detectors (LAPPD). They offer fast timing in the range of 30-100 ps rather than the 2 ns typical for large PMTs. They also offer a spatial

resolution of less 5 mm versus 25-50 cm typical of standard PMTs. They are considered an imaging detector rather than single pixel (PMT) and suffer less from magnetic field effects such that no magnetic compensation system necessary, which can become costly for large detectors. One of the most exciting possibility is the  $\pi^0$  background suppression for GeV scale interactions by gamma separation in both space and time. Commercialization efforts and further R&D are ongoing [8].

## **Light output improvements, Water-base liquid scintillator WbLS**

Ongoing research in developing surfactant that are necessary to emulsify (or aggregate) organic liquid scintillator into the water solvent and Linear Alkylbenzene Sulfonic acid (LAS); early results show a stable first-generation WbLS. The goal are (a) measure below Cherenkov threshold (b) not too much scintillation to lose track information and (c) improve energy resolution [10].

## **CHERENKOV EXPERIMENTS TO MEASURE NEUTRONS**

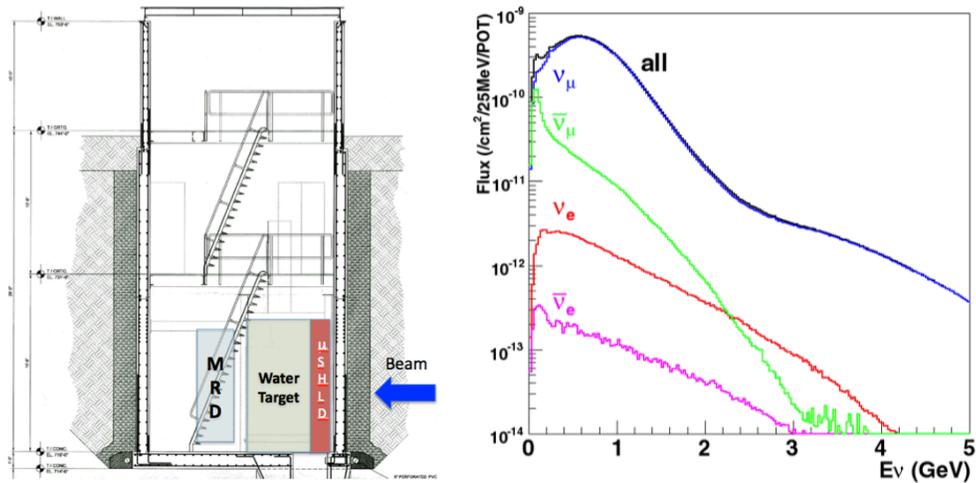
The use of water Cherenkov imaging detectors to observe neutrons is not unprecedented, for example the SNO experiment was built in the mindset of measuring neutrons. The  $D_2O$  media enabled neutron capture on deuteron which produces gammas (a 6.3 MeV signature) above the energy threshold of typical water Cherenkov energy threshold. It is important to note that the absence of hydrogen is paramount, since neutron capture on hydrogen has a high cross-section and the resulting signature (a 2.2 MeV signature) is below the energy threshold of typical Water Cherenkov detectors leading to an “invisible” capture.  $D_2O$  is expensive and it is not realistic to expect new detector to consider this an option. In this optic, another approach is required to bypass the “invisible” neutron capture on hydrogen and the use Gadolinium (Gd) isotopes to capture neutrons (a 7.9 MeV signature) is a natural choice. The cross section is greater than hydrogen and alternatively, the capture time (27  $\mu$ s) is an order of magnitude smaller than on hydrogen, which can enable precise measurement of burst of anti-neutrinos that are typical of supernovas. However, while the development of Gd technology has been proven in a liquid scintillator setting, there are still challenges in the solubility of this metal in water.

## **EGADS**

These challenges are being address with first the Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande (GADZOOK) experiment and now the Evaluating Gadolinium’s Action on Detector Systems (EGADS) experiment [9]. EGADS is 200 ton (6.5  $\times$  6.5 m) water tank with 240 50-cm PMTs. Results from EGADS have shown stable light levels at 20-meters with water fully loaded with Gd. This represent 0.88% of light reduction compared to pure water of Super-Kamiokande. The filtration system has not shown lost of Gd after more than 100 complete cycles.

## **WATCHMAN**

The Nuclear Non-Proliferation (NNP) community as shown interest in the development of water-based anti-neutrino detection. A proposal is currently being drafted to National Nuclear Security Agency (NNSA), which is a subset of the US Department Of Energy (DOE). The proposal is to deploy a kiloton water-based Cherenkov detector at 1 to 10 km standoff at 0.1 to 10 GWt nuclear reactor. This program may serve as the link between the work R&D work being made at EGADS and the implementation at Hyper-Kamiokande. All light collector options described in this document are also under consideration. These results will affect the technology decision for the 1 kiloton detector which is set at late 2014 to early 2015.



**FIGURE 2.** On the left is ANNIE at the SciBooNE Hall. On the right is the neutrino spectrum expected at ANNIE.

## ANNIE

A dedicated experiment called Atmospheric Neutrino Neutron Interaction Exploration (ANNIE) is proposed to measure the neutron yield from MeV to GeV scale which would use existing SciBooNE hall in the FNAL booster beam has been proposed. As stated previously, the tagging of FSI neutrons from atmospheric neutrino may dramatically reduce backgrounds to proton decay searches. The detector is composed of a  $3\text{ m} \times 3\text{ m} \times 2\text{ m}$  water volume which acts as the target for the beam of neutrinos enabling the measurement of the neutron yield on  $^{16}\text{O}$ ; there is the possibility change the water target to  $\text{CH}_2$  to measure the neutron yield on  $^{12}\text{C}$ . Muon Range Detector (MRD) doped with gadolinium is composed of 12 2-inch thick iron plates sandwiched between 13 scintillation panels with a 362 two-inch PMTs readout will characterize the muon energy.

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